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Differential Astrometry with the Keck Interferometer

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Abstract. A key thrust of NASA's Origins program is the detection and characterization of planetary systems around other stars. The Keck Interferometer (KI) is being developed jointly by the Jet Propulsion Laboratory and the W.M. Keck Observatory as part of NASA's Origins Program. The KI will combine the two 10-m Keck telescopes with four proposed 1.8-m outrigger telescopes as an interferometric array capable of addressing a broad range of astronomical science. KI will perform pairwise and multi-way Michelson beam combination of light from the two 10m Keck Telescopes and a set of four 1.8-m "outrigger" telescopes.

Among the KI's high priority science programs will be the differential astrometric detection of planetary companions to nearby stars. KI will perform narrow-angle differential astrometry by simultaneous co-phasing and fringe tracking two stars within an isoplanatic patch. The expected astrometric performance of the KI is 30 microarcseconds, capable of detecting planets down to Uranus-mass around nearby solar-analog stars.

1. Introduction

The Keck Interferometer (KI) is being developed jointly by NASA's Jet Propulsion Laboratory and the W.M. Keck Observatory under the auspices of NASA's Origins Program (JPL 1999b). The KI will combine the two 10-m Keck telescopes with four 1.8-m outrigger telescopes as an interferometric array capable of addressing a broad range of astronomical science. KI instrumentation will include two-way combiners for co-phasing and single-baseline measurements, a nulling combiner for high-dynamic range measurements, and a multi-way imaging combiner. Primary science objectives for KI include the characterization of zodiacal dust around other stars, detection of hot exo-Jupiters and brown dwarfs through multi-color differential-phase measurements, astrometric searches for planets down to Uranus-mass, and a wide range of infrared imaging. Further

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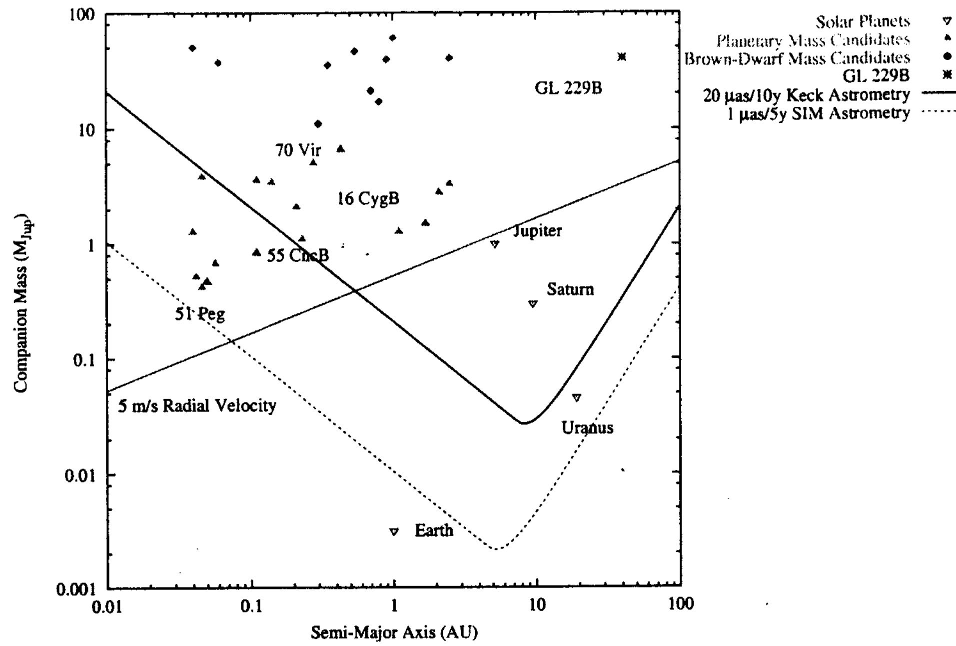

Figure 1. Phase Space of Planetary Detection Probed By Radial Velocity and Astrometric Techniques For a Solar-Type Star at 10 pc.

details are available elsewhere (Colavita et al. 1998, van Belle et al. 1998, Booth et al. 1999, JPL 1999a).

In this paper we will describe differential astrometry for exo-planet detection with the Keck Interferometer. By now it is well established that gravitational reflex motions are a compelling method to infer the presence of planetary-mass companions to nearby stars; to date roughly thirty planetary-mass objects and one multiple-planet system are inferred by spectroscopic detection of radial velocity reflex motions of FGK stars (Mayor & Queloz 1995, Marcy & Butler 1998, Marcy et al. 1999, Schneider 1999). As is well known (e.g. Shao & Colavita 1992), highly accurate astrometry probes the two-dimensional transverse reflex motion of the parent star, and establishes the orbital inclination and mass (formally mass ratio to the parent) of a companion planetary-mass object.

Figure 1 gives an example of the exo-planet detection phase space probed by astrometric and radial velocity techniques in the context of a solar-mass star at a presumed distance of 10 pc. Radial velocity (RV) detection sensitivities (indicated by the red line for a 5 m s^{-1} precision), and typical ground-based (20 μas – 10 yr indicated by the solid black line) and space-based (1 μas – 5 yr indicated by the dotted blue line) astrometric detection sensitivities are illustrated. Shown for reference are the positions of solar planets (Jupiter, Saturn, Uranus, Earth), exo-planet candidates, brown dwarf-mass candidates, and GL 229B in this space. Figure 1 makes two points. First the two detection techniques, RV and astrometric, are highly complementary. One can see the current set of exo-planet candidates are almost certainly biased from the parent exo-planet distribution by strong selection effects of the (RV) detection technique towards short-period orbits. Likewise astrometric detection has selection effects toward long (but not too long) period orbits. Taken together these two techniques do an excellent job of probing the likely phase space of planetary-mass companions to stars. Second, one can see from the diagram the range of RV and astrometric precisions required to search for the planetary-mass companions.

2. Observational Mode and Operating Parameters

Interferometric astrometry follows from the observation that the wide-band fringe position of a star occurs when the pathlengths of starlight are equal at the interferometer detector. In vacuum the wide-band fringe delay d for a star in a unit vector direction $\hat{\mathbf{s}}$ measured by an interferometer baseline $\mathbf{B}$ is given by the *astrometric equation* (Mozurkewich et al. 1988, Shao et al. 1990):

$$d = \hat{\mathbf{s}} \cdot \mathbf{B} + C \tag{1}$$

where C is a possible constant or *bias* between true equilibrated optical path and the instantaneous zero point a (laser or other) metrology system used to measure pathlengths in the interferometer. Given two stars in directions $\hat{\mathbf{s}}_1$ and $\hat{\mathbf{s}}_2$, fringe measurements on both stars with a common delay bias measure a differential delay Δd as proxy for the astrometric separation $\Delta \mathbf{s}$:

$$\Delta d \equiv d_2 - d_1 = (\hat{\mathbf{s}}_2 \cdot \mathbf{B} + C) - (\hat{\mathbf{s}}_1 \cdot \mathbf{B} + C) = \Delta \mathbf{s} \cdot \mathbf{B} \tag{2}$$

The atmosphere perturbs the instantaneous fringe position of a star from its nominal value; these perturbations are on the order of tens of microns for long-baseline interferometers. However as noted by Shao and Colavita these perturbations are highly correlated over narrow fields, and the time required to integrate these path fluctuations to achieve tens of microarcsecond (10^{-6} arcsecond, μas) relative astrometric measurements is tractable (Shao & Colavita 1992). To exploit this instantaneous correlation the delay measurements must be made *simultaneously*, hence it is necessary to couple two interferometers together to make the required delay measurements.

A schematic of the KI differential astrometry measurement technique is given in Figure 2. Light from two stars (typically a bright *primary* target star and a fainter *secondary* reference star) is collected by a pair of KI outrigger telescopes, and separated into independent primary and secondary beams at a focus. These two sets of beams are then separately delayed to equilibrate their paths and routed to two separate beam combiners to measure and track the broadband fringes. Laser metrology to measure the optical path difference (OPD) in the primary and secondary beam trains is injected at each of the beam combiners, and polarization and modulation-encoded to allow primary/secondary separation on return. The differential metrology OPD (plus fringe phase delay) difference secondary - primary is exactly the differential path delay observable used in applying Eq. 2 to perform the astrometric measurement between the primary and secondary stars.

In order to obtain more complete sky coverage for a given primary star it is desirable to forward pathlength tracking information measured on the bright

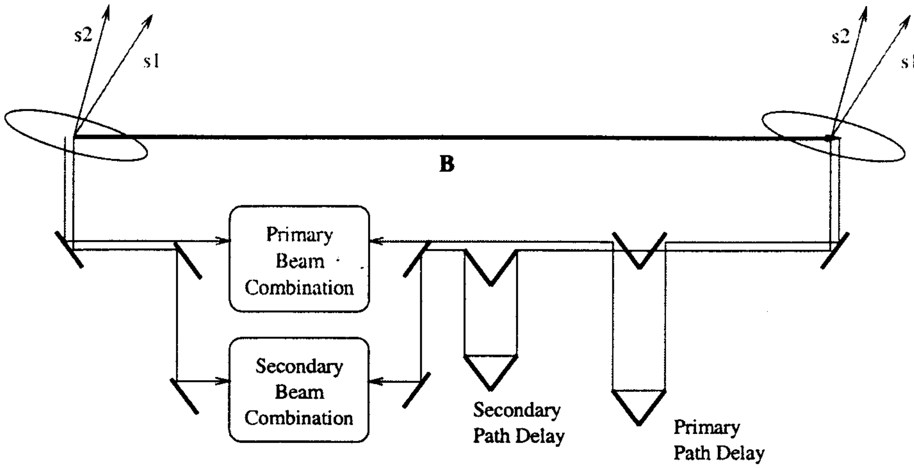

Figure 2. Schematic of KI Differential Astrometry Measurement

primary star to the pathlength control for the dimmer secondary star; this allows the secondary fringe tracker to operate with a syntheticly long coherence time and track significantly fainter stars. The long synthetic coherence time is possible so long as the pathlength fluctuations of primary and secondary stars are highly correlated, and this typically true when the two stars are within an isoplanatic patch on the sky – typically 20 – 30 arcseconds radius at the Keck site in the near-infrared K (2.2 μm) band. We estimate our limiting magnitudes for primary and secondary fringe tracking to be approximately 8.5 and 17 respectively. Based on these sensitivities and galactic star count models we expect the sky coverage for KI astrometry to be in the 40 – 50% range.

Because an individual KI astrometric measurement is inherently (almost) one-dimensional along the sky projection of the baseline (Eqs. 1 and 2), the KI outrigger geometry is arranged to allow the formation of two quasi-orthogonal astrometric baselines for astrometric error isotropy (Colavita et al. 1998, van Belle et al. 1998, Booth et al. 1999). The KI astrometric measurement performance is set by a number of factors, including photon and detector noise (particularly on the dimmer reference star), fringe tracker performance, atmospheric conditions, and astrometric baseline stability and calibration. We estimate that KI will achieve an astrometric performance of 30 μas in a one-hour integration.

Table 1 gives a summary of the pertinent operational parameters for KI astrometry.

3. Discussion

The current KI implementation schedule calls for outrigger installation and astrometry debugging during 2002, with an expectation that astrometry scientific operations will commence in 2003. The astrometric mode is one of the fundamental motivations for building KI, and a planet search/characterization astrometry program has been identified by NASA as one of three KI Key Projects. NASA expects to issue an Announcement of Opportunity for the KI astrometry project

KI Astrometric Parameter	Value
Operating Wavelength	K (2 – 2.4 μm)
Limiting Primary Magnitude	$K \sim 8.5$
Limiting Secondary Magnitude	$K \sim 17$
Isoplanatic Patch Size	20 – 30"
Sky Coverage	40 – 50%
Astrometric Baseline Length	$\sim$ 120 m
Astrometric Performance ($\sqrt{hr}$)	30 μas

Table 1. KI Astrometry Mode Operational Parameters

in mid 2001, in order to have the selected astrometry key science team under contract and participating with the JPL/WMKO KI implementation team during the astrometry debugging.

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References

Booth, A. et al. 1999, these proceedings.

Colavita, M. 1994, A&A 283, 1027.

Colavita, M. et al. 1998, Proc SPIE 3350-30.

JPL 1999a, http://huey.jpl.nasa.gov/keck

JPL 1999b, http://origins.jpl.nasa.gov

Marcy, G. and Butler, P. 1998, ARA&A 36, 51.

Marcy, G., Butler, P., and Fischer, D. 1999, AAS 194.1402.

Mayor, M. and Queloz, D. 1995, Nature 378, 355.

Mozurkewich, D. et al. 1988, AJ 95, 1269.

Schneider, J. 1999, http://www.obspm.fr/encycl/encycl.html.

Shao, M. et al. 1990, AJ 100, 1701.

Shao, M. and Colavita, M. 1992, A&A 262, 353.

van Belle, G. et al. 1998, Proc SPIE 3350-104.